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Term: l1 and (normaliz$6) same (interpolation)

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Search History

DATE: Tuesday, February 19, 2002 Printable Copy Create Case

Set Name side by side	Query
	DB=USPT,PGPB,TDBD; PLUR=YES; OP=ADJ
L5	l1 and (normaliz$6) same (interpolation)
L4	l1 and (normaliz$6) same (linear interpolation)
L3	l1 and (normaliz$6) same (tetrahedron or tetrahedral)
	DB=TDBD,PGPB,USPT; PLUR=YES; OP=ADJ
L2	l1 and normaliz$6
L1	(CANON-KABUSHIKI-KAISHA..ASN. | CANON-SALES-CO.-AND-SEMICONDUCTOR-PROCESS-LABORATORY-CO.-LTD..ASN | CANON-SALES-CO.-INC..ASN. | "CANONKABUSHIKI".ASN. | "CANON".ASN. | CANON-KABUSHIKI-KAISHA..ASN. | CANON-SALES-CO.-AND-SEMICONDUCTOR-PROCESS-LABORATORY-CO.-LTD..ASN | CANON-SALES-CO.-INC..ASN. | "CANONDALE".ASN.)!

END OF SEARCH HISTORY

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Search Results - Record(s) 1 through 10 of 11 returned.

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1. Document ID: US 6023351 A

L5: Entry 1 of 11 File: USPT Feb 8, 2000

US-PAT-NO: 6023351
DOCUMENT-IDENTIFIER: US 6023351 A

TITLE: Regularized printer LUT with improved accuracy

DATE-ISSUED: February 8, 2000

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Newman; Todd	Palo Alto	CA		

US-CL-CURRENT: 358/524; 358/522, 358/523, 358/530

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

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2. Document ID: US 6021388 A

L5: Entry 2 of 11 File: USPT Feb 1, 2000

US-PAT-NO: 6021388
DOCUMENT-IDENTIFIER: US 6021388 A

TITLE: Speech synthesis apparatus and method

DATE-ISSUED: February 1, 2000

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Otsuka; Mitsuru	Iwatsuki			JPX
Ohora; Yasunori	Yokohama			JPX
Aso; Takashi	Yokohama			JPX
Okutani; Yasuo	Yokohama			JPX

US-CL-CURRENT: 704/268; 704/269

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

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3. Document ID: US 5809181 A

L5: Entry 3 of 11 File: USPT Sep 15, 1998

US-PAT-NO: 5809181
DOCUMENT-IDENTIFIER: US 5809181 A

TITLE: Color conversion apparatus

DATE-ISSUED: September 15, 1998

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Metcalfe; James Robert	Collaroy Plateau			AUX

US-CL-CURRENT: 382/276; 358/523, 358/525, 382/167

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

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4. Document ID: US 5745650 A

L5: Entry 4 of 11 File: USPT Apr 28, 1998

US-PAT-NO: 5745650
DOCUMENT-IDENTIFIER: US 5745650 A

TITLE: Speech synthesis apparatus and method for synthesizing speech from a character series comprising a text and pitch information

DATE-ISSUED: April 28, 1998

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Otsuka; Mitsuru	Yokohama			JPX
Ohora; Yasunori	Yokohama			JPX
Aso; Takashi	Yokohama			JPX
Fukada; Toshiaki	Yokohama			JPX

US-CL-CURRENT: 704/260; 704/201, 704/205, 704/206, 704/207, 704/211, 704/258, 704/264, 704/267, 704/268

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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5. Document ID: US 5719789 A

L5: Entry 5 of 11 File: USPT Feb 17, 1998

US-PAT-NO: 5719789
DOCUMENT-IDENTIFIER: US 5719789 A

TITLE: Method of and apparatus for detecting an amount of displacement

DATE-ISSUED: February 17, 1998

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Kawamata; Naoki	Utsunomiya			JPX

US-CL-CURRENT: 702/189; 356/499

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw. Desc | Image

6. Document ID: US 5432891 A

L5: Entry 6 of 11 File: USPT Jul 11, 1995

US-PAT-NO: 5432891
DOCUMENT-IDENTIFIER: US 5432891 A

TITLE: Image processing method and apparatus

DATE-ISSUED: July 11, 1995

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Onodera; Ken	Yokohama			JPX

US-CL-CURRENT: 358/1.15; 358/1.16

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw. Desc | Image

7. Document ID: US 5351137 A

L5: Entry 7 of 11 File: USPT Sep 27, 1994

US-PAT-NO: 5351137
DOCUMENT-IDENTIFIER: US 5351137 A

TITLE: Pixel density converting apparatus

DATE-ISSUED: September 27, 1994

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Kato; Masami	Sagamihara			JPX
Kato; Takao	Yokohama			JPX
Hashimoto; Yasunori	Yokohama			JPX

US-CL-CURRENT: 358/457; 358/456

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw. Desc | Image

8. Document ID: US 5319471 A

L5: Entry 8 of 11 File: USPT Jun 7, 1994

US-PAT-NO: 5319471

DOCUMENT-IDENTIFIER: US 5319471 A

TITLE: Image transmitting apparatus having improved coding of multi-valued image data

DATE-ISSUED: June 7, 1994

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Takei; Masahiro	Tokyo			JPX
Takayama; Tadashi	Tokyo			JPX
Horii; Hiroyuki	Tokyo			JPX
Kimura; Norio	Tokyo			JPX

US-CL-CURRENT: 358/451; 358/408, 358/426

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

☐ 9. Document ID: US 5289293 A

L5: Entry 9 of 11 File: USPT Feb 22, 1994

US-PAT-NO: 5289293
DOCUMENT-IDENTIFIER: US 5289293 A

TITLE: Pixel density conversion and processing

DATE-ISSUED: February 22, 1994

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Kato; Masami	Sagamihara			JPX
Kato; Takao	Yokohama			JPX
Hashimoto; Yasunori	Yokohama			JPX

US-CL-CURRENT: 358/457; 358/456

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

☐ 10. Document ID: US 5220629 A

L5: Entry 10 of 11 File: USPT Jun 15, 1993

US-PAT-NO: 5220629
DOCUMENT-IDENTIFIER: US 5220629 A

TITLE: Speech synthesis apparatus and method

DATE-ISSUED: June 15, 1993

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Kosaka; Tetsuo	Yokohama			JPX
Sakurai; Atsushi	Yokohama			JPX
Tamura; Junichi	Tokyo			JPX
Ohora; Yasunori	Tokyo			JPX
Fujita; Takeshi	Yokohama			JPX
Aso; Takashi	Yokohama			JPX
Kawasaki; Katsuhiko	Machida			JPX

US-CL-CURRENT: 704/260

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC

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Terms	Documents
l1 and (normaliz$6) same (interpolation)	11

Display Format: Change Format

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Search Results - Record(s) 11 through 11 of 11 returned.

11. Document ID: US 5202670 A

L5: Entry 11 of 11 File: USPT Apr 13, 1993

US-PAT-NO: 5202670
DOCUMENT-IDENTIFIER: US 5202670 A

TITLE: Image processing apparatus

DATE-ISSUED: April 13, 1993

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Oha; Shinichi	Tokyo			JPX

US-CL-CURRENT: 345/671; 345/606, 358/451, 382/299

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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Terms	Documents
l1 and (normaliz$6) same (interpolation)	11

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normalize and grid points

Search Again

Results:
Journal or Magazine = **JNL** Conference = **CNF** Standard = **STD**

1 **Fuzzy approximation via grid point sampling and singular value decomposition**
Yeung Yam
Systems, Man and Cybernetics, Part B, IEEE Transactions on , Volume: 27 Iss
Dec. 1997
Page(s): 933 -951

[Abstract] [PDF Full-Text (936 KB)] **JNL**

2 **Singular value-based identification of fuzzy system**
Yeung Yam
Decision and Control, 1997., Proceedings of the 36th IEEE Conference on , Vo
1997
Page(s): 3341 -3346 vol.4

[Abstract] [PDF Full-Text (480 KB)] **CNF**

3 **A comparison of rotation-based methods for iterative reconstruction algorithms**
Di Bella, E.V.R.; Barclay, A.B.; Eisner, R.L.; Schafer, R.W.
Nuclear Science, IEEE Transactions on , Volume: 43 Issue: 6 Part: 2 , Dec. 19
Page(s): 3370 -3376

[Abstract] [PDF Full-Text (148 KB)] **JNL**

4 **Comparison of rotation-based methods for iterative reconstruction algorithms**
Di Bella, E.V.R.; Barclay, A.B.; Eisner, R.L.; Schafer, R.W.

Di Bella, E.V.R.; Barclay, A.B.; Eisner, R.L.; Schafer, R.W.
Nuclear Science Symposium and Medical Imaging Conference Record, 1995.,
, Volume: 2 , 1995
Page(s): 1146 -1150 vol.2

[Abstract] [PDF Full-Text (528 KB)] **CNF**

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Search Results - Record(s) 1 through 1 of 1 returned.

☑ 1. Document ID: US 6295137 B1

L2: Entry 1 of 1 File: USPT Sep 25, 2001

US-PAT-NO: 6295137
DOCUMENT-IDENTIFIER: US 6295137 B1

TITLE: Method of color correction using multi-level halftoning

DATE-ISSUED: September 25, 2001

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Balasubramanian; Thyagarajan	Webster	NY		

US-CL-CURRENT: 358/1.9; 358/456, 358/518, 358/523, 358/534

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | Claims | KWIC | Draw Desc | Image

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Terms	Documents
tetrahedral interpolation same normaliz$6	1

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L Number	Hits	Search Text	DB	Time stamp
1	471	(data conversion) near (normalization)	USPAT	2002/02/19 17:06
3	0	(data conversion) near (normalization) near (large number$1 or big number$1 or huge number$1) near (integer$1)	USPAT	2002/02/19 17:07
2	2	(data conversion) near (normalization) near (large number or big number or huge number)	USPAT	2002/02/19 17:10
4	0	(data conversion) near (normalization) near (integer$1)	USPAT	2002/02/19 17:11
5	12	(normalization) near (integer$1)	USPAT	2002/02/19 17:23
6	69	(normaliz$5) near (integer$1)	USPAT	2002/02/19 17:23
7	3	(normaliz$5) near (integer$1) near (data conversion)	USPAT	2002/02/19 17:25
8	20	(normaliz$5) near (operation) near (data conversion)	USPAT	2002/02/19 18:02
9	475096	tetrahedral linear interpolation	USPAT	2002/02/19 18:03
11	1	(tetrahedral linear interpolation) near (normalization) near (operation$1)	USPAT	2002/02/19 18:04
10	60	(tetrahedral linear interpolation) near (normalization)	USPAT	2002/02/19 18:23
12	0	(tetrahedral linear interpolation) near (normalization) near (multiple large integer$1)	USPAT	2002/02/19 18:24
13	928	(normalization) same (power of ((data conversion) near (normalization) near (large number or big number or huge number)))	USPAT	2002/02/19 18:24
14	0	(normalization) same (power of ((data conversion) near (normalization) near (large number or big number or huge number))) same (tetrahdral or tetrahedron)	USPAT	2002/02/19 18:25
15	89	(normalization) same (power of ((data conversion) near (normalization) near (large number or big number or huge number))) same (linear intepolation)	USPAT	2002/02/19 18:25
16	100	(normalization) same (power of ((data conversion) near (normalization) near (large number or big number or huge number))) same (linear interpolation)	USPAT	2002/02/19 18:25
17	11	(normalization) same (power of ((data conversion) near (normalization) near (large number or big number or huge number))) same (linear interpolation) same (grid point$1)	USPAT	2002/02/19 18:26

	U	1	Document ID	Issue Date	Pages
1	☐	☐	US 6115338 A	20000905	82
2	☐	☐	US 6072761 A	20000606	53
3	☐	☐	US 6021388 A	20000201	53
4	☐	☐	US 5828705 A	19981027	14
5	☐	☐	US 5825579 A	19981020	23
6	☐	☐	US 5732055 A	19980324	80
7	☐	☐	US 5684920 A	19971104	34
8	☐	☐	US 5248997 A	19930928	7
9	☐	☐	US 4905204 A	19900227	21
10	☐	☐	US 4882713 A	19891121	21
11	☐	☐	US 4719585 A	19880112	14

	Title	Current OR	Current XRef
1	Optical storage apparatus	369/47.52	369/116 ; 369/47.53
2	Optical storage apparatus having an automatic laser power control with light emission fine control	369/116	369/53.26 ; 369/53.27
3	Speech synthesis apparatus and method	704/268	704/269
4	Carrier tracking technique and apparatus having automatic flywheel/tracking/reacquisition control and extended signal to noise ratio	375/326	375/316 ; 375/322 ; 375/324 ; 375/354 ; 375/355
5	Disk drive servo sensing gain normalization and linearization	360/77.08	360/77.02
6	Optical storage apparatus	369/53.26	369/116
7	Acoustic signal transform coding method and decoding method having a high efficiency envelope flattening method therein	704/203	704/201 ; 704/204 ; 704/219 ; 704/220 ; 704/258 ; 704/262
8	Facet reflectance correction in a polygon scanner	347/261	359/217
9	Method of weighting a trace stack from a plurality of input traces	367/62	367/38 ; 702/17
10	Method for noise suppression in the stacking of seismic traces	367/47	367/62 ; 702/17
11	Dividing cubes system and method for the display of surface structures contained within the interior region of a solid body	345/424	345/419 ; 345/426 ; 600/425

	Retrieval Classif	Inventor	S	C	P	2	3	4	5
1		Masaki, Takashi , et al.	☒	☐	☐	☐	☐	☐	☐
2		Tani, Hiroshi	☒	☐	☐	☐	☐	☐	☐
3		Otsuka, Mitsuru , et al.	☒	☐	☐	☐	☐	☐	☐
4		Kroeger, Brian W. , et al.	☒	☐	☐	☐	☐	☐	☐
5		Cheung, Wayne Leung , et al.	☒	☐	☐	☐	☐	☐	☐
6		Masaki, Takashi , et al.	☒	☐	☐	☐	☐	☐	☐
7		Iwakami, Naoki , et al.	☒	☐	☐	☐	☐	☐	☐
8		Summers, Drew D.	☒	☐	☐	☐	☐	☐	☐
9		Hughes, Phillip A.	☒	☐	☐	☐	☐	☐	☐
10		Hughes, Philip A.	☒	☐	☐	☐	☐	☐	☐
11		Cline, Harvey E. , et al.	☒	☐	☐	☐	☐	☐	☐

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Search Results - Record(s) 1 through 10 of 11 returned.

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1. Document ID: US 6023351 A

L5: Entry 1 of 11 File: USPT Feb 8, 2000

US-PAT-NO: 6023351
DOCUMENT-IDENTIFIER: US 6023351 A

TITLE: Regularized printer LUT with improved accuracy

DATE-ISSUED: February 8, 2000

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Newman; Todd	Palo Alto	CA		

US-CL-CURRENT: 358/524; 358/522, 358/523, 358/530

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | Claims | KWIC | Draw Desc | Image

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2. Document ID: US 6021388 A

L5: Entry 2 of 11 File: USPT Feb 1, 2000

US-PAT-NO: 6021388
DOCUMENT-IDENTIFIER: US 6021388 A

TITLE: Speech synthesis apparatus and method

DATE-ISSUED: February 1, 2000

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Otsuka; Mitsuru	Iwatsuki			JPX
Ohora; Yasunori	Yokohama			JPX
Aso; Takashi	Yokohama			JPX
Okutani; Yasuo	Yokohama			JPX

US-CL-CURRENT: 704/268; 704/269

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | Claims | KWIC | Draw Desc | Image

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3. Document ID: US 5809181 A

L5: Entry 3 of 11 File: USPT Sep 15, 1998

US-PAT-NO: 5809181
DOCUMENT-IDENTIFIER: US 5809181 A

TITLE: Color conversion apparatus

DATE-ISSUED: September 15, 1998

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Metcalfe; James Robert	Collaroy Plateau			AUX

US-CL-CURRENT: 382/276; 358/523, 358/525, 382/167

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | Claims | KWIC
Draw Desc | Image

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4. Document ID: US 5745650 A

L5: Entry 4 of 11 File: USPT Apr 28, 1998

US-PAT-NO: 5745650
DOCUMENT-IDENTIFIER: US 5745650 A

TITLE: Speech synthesis apparatus and method for synthesizing speech from a character series comprising a text and pitch information

DATE-ISSUED: April 28, 1998

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Otsuka; Mitsuru	Yokohama			JPX
Ohora; Yasunori	Yokohama			JPX
Aso; Takashi	Yokohama			JPX
Fukada; Toshiaki	Yokohama			JPX

US-CL-CURRENT: 704/260; 704/201, 704/205, 704/206, 704/207, 704/211, 704/258, 704/264, 704/267, 704/268

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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5. Document ID: US 5719789 A

L5: Entry 5 of 11 File: USPT Feb 17, 1998

US-PAT-NO: 5719789
DOCUMENT-IDENTIFIER: US 5719789 A

TITLE: Method of and apparatus for detecting an amount of displacement

DATE-ISSUED: February 17, 1998

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Kawamata; Naoki	Utsunomiya			JPX

US-CL-CURRENT: 702/189; 356/499

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☑ 6. Document ID: US 5432891 A

L5: Entry 6 of 11 File: USPT Jul 11, 1995

US-PAT-NO: 5432891
DOCUMENT-IDENTIFIER: US 5432891 A

TITLE: Image processing method and apparatus

DATE-ISSUED: July 11, 1995

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Onodera; Ken	Yokohama			JPX

US-CL-CURRENT: 358/1.15; 358/1.16

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☑ 7. Document ID: US 5351137 A

L5: Entry 7 of 11 File: USPT Sep 27, 1994

US-PAT-NO: 5351137
DOCUMENT-IDENTIFIER: US 5351137 A

TITLE: Pixel density converting apparatus

DATE-ISSUED: September 27, 1994

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Kato; Masami	Sagamihara			JPX
Kato; Takao	Yokohama			JPX
Hashimoto; Yasunori	Yokohama			JPX

US-CL-CURRENT: 358/457; 358/456

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☑ 8. Document ID: US 5319471 A

L5: Entry 8 of 11 File: USPT Jun 7, 1994

US-PAT-NO: 5319471

DOCUMENT-IDENTIFIER: US 5319471 A

TITLE: Image transmitting apparatus having improved coding of multi-valued image data

DATE-ISSUED: June 7, 1994

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Takei; Masahiro	Tokyo			JPX
Takayama; Tadashi	Tokyo			JPX
Horii; Hiroyuki	Tokyo			JPX
Kimura; Norio	Tokyo			JPX

US-CL-CURRENT: 358/451; 358/408, 358/426

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☑ 9. Document ID: US 5289293 A

L5: Entry 9 of 11 File: USPT Feb 22, 1994

US-PAT-NO: 5289293
DOCUMENT-IDENTIFIER: US 5289293 A

TITLE: Pixel density conversion and processing

DATE-ISSUED: February 22, 1994

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Kato; Masami	Sagamihara			JPX
Kato; Takao	Yokohama			JPX
Hashimoto; Yasunori	Yokohama			JPX

US-CL-CURRENT: 358/457; 358/456

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☑ 10. Document ID: US 5220629 A

L5: Entry 10 of 11 File: USPT Jun 15, 1993

US-PAT-NO: 5220629
DOCUMENT-IDENTIFIER: US 5220629 A

TITLE: Speech synthesis apparatus and method

DATE-ISSUED: June 15, 1993

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Kosaka; Tetsuo	Yokohama			JPX
Sakurai; Atsushi	Yokohama			JPX
Tamura; Junichi	Tokyo			JPX
Ohora; Yasunori	Tokyo			JPX
Fujita; Takeshi	Yokohama			JPX
Aso; Takashi	Yokohama			JPX
Kawasaki; Katsuhiko	Machida			JPX

US-CL-CURRENT: 704/260

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☑ 11. Document ID: US 5202670 A

L5: Entry 11 of 11 File: USPT Apr 13, 1993

US-PAT-NO: 5202670
DOCUMENT-IDENTIFIER: US 5202670 A

TITLE: Image processing apparatus

DATE-ISSUED: April 13, 1993

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Oha; Shinichi	Tokyo			JPX

US-CL-CURRENT: 345/671; 345/606, 358/451, 382/299

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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Term: tetrahedral interpolation same normaliz$6

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Dynamic simulation model for two-phase mutually coupled reluctance machine

- *Reeve, J.M.; Pollock, C.*
Dept. of Eng., Leicester Univ., UK

This paper appears in: Industry Applications Conference, 2001. Thirty-Sixth IAS Meeting. Conference Record of the 2001 IEEE
On page(s): 40 - 47 vol.1
30 Sept.-4 Oct. 2001
Chicago, IL, USA
2001
Volume: 1
ISBN: 0-7803-7114-3
IEEE Catalog Number: 01CH37248
Number of Pages: 4 vol.xxxvii+2743
References Cited: 23
INSPEC Accession Number: 7081518

Abstract:
This paper presents a simple yet robust and flexible dynamic simulation model
two-phase reluctance type machines. Normalized electromagnetic properties of
lamination geometry, the 'flux map', are obtained using nonlinear magnetostat
element analysis (FEA). A data conversion algorithm is developed to convert th
a form suitable for voltage driven dynamic simulation, i.e. a two-phase coupled
flux-MMF-position characterization. System dynamic equations are derived and
with the Gauss-Seidel method using the converted data without further need fo
Comparison with experimental results for an 8/4 flux switching machine with a
shows good agreement. This model can be used to rapidly simulate any windin
configuration or excitation scheme based upon the characterized geometry and
especially suitable for commercial design.

Index Terms:
reluctance machines; machine theory; electromagnetic fields; laminations; ma
iterative methods; finite element analysis; two-phase mutually coupled relucta
machines; dynamic simulation model; electromagnetic properties; lamination g
flux map; nonlinear magnetostatic finite element analysis; data conversion algo
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characterization; dynamic equations; Gauss-Seidel method; winding configurat
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SEARCH RESULTS [PDF Full-Text (304 KB)]

Recursive least-squares lattices and trigonometry in the spherical triangle

- *Desbouvries, F.*
Inst. Nat. des Telecommun., Evry, France

This paper appears in: Acoustics, Speech, and Signal Processing, 1993. ICASSP IEEE International Conference on
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27-30 April 1993
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1993
Volume: 3
ISBN: 0-7803-0946-4
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References Cited: 13
INSPEC Accession Number: 4777675

Abstract:
The three fundamental planar biorthogonalization steps which underlie the geo derivation of the fast recursive least squares (FRLS) adaptive lattices are gathe unit-length 3-D tetrahedron. The inverse of Yule's PARCOR Identity (YPII) then nice geometric interpretation in terms of projections into this tetrahedron. Sinc tetrahedrons are closely related to spherical triangles, YPII is recognized as the fundamental 'cosine law' of spherical trigonometry. In that framework, the angle-normalized RLS lattice recursions happen to be one particular solution to six spherical triangle problems. The practical interest of this geometric interpre that one can take advantage of spherical trigonometry to derive unnoticed recu among RLS quantities. This leads, for instance, to an original 'dual' version of Y

Index Terms:
trigonometry; planar biorthogonalization steps; recursive least squares; adapti geometric interpretation; spherical trigonometry; adaptive filters; computation geometry; filtering and prediction theory; least squares approximations

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RECURSIVE LEAST-SQUARES LATTICES AND TRIGONOMETRY IN THE SPHERICAL TRIANGLE

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ABSTRACT

The 3 fundamental planar biorthogonalization steps which underlie the geometric derivation of the FRLS adaptive lattices are gathered into a unit-length 3D tetrahedron. The inverse of Yule's PARCOR Identity (YPII) then admits a nice geometric interpretation in terms of projections into this tetrahedron. Since tetrahedrons are closely related to spherical triangles, YPII is recognized as the fundamental "cosine law" of spherical trigonometry. In that framework, the angle-normalized RLS lattice recursions happen to be one particular solution to one of the six spherical triangle problems. The practical interest of this brand new geometric interpretation is that we can take advantage of the well-trodden path of spherical trigonometry to derive unoticed recursions among RLS quantities. This leads, for instance, to an original "dual" version of YPII.

1 - INTRODUCTION

Fast Recursive Least-Squares (FRLS) prewindowed (PW) algorithms are well known to exist under three different structures : transversal, lattice, and QRD-based filters. The Recursive Least-Squares Lattice (RLSL) has been known for a long time now [1]. Later on, Lee et al showed that the RLSL basic cell reduces to a recursion among 3 variables only, when appropriate normalization is performed. The incoming entries are the forward and delayed backward "double-" or "angle-" normalized prediction errors, $\bar{\varepsilon}_{n-1}^{t}$ and $\bar{\eta}_{n-1}^{t-1}$, at order $n-1$, together with the n^{th} order PARCOR ρ_n^{t-1} at time $t-1$. The algorithm first updates the PARCOR, then computes the forward and backward errors at order n (1-a,b,c) :

$$\rho_n^{t} = \bar{\varepsilon}_{n-1}^{t}(\bar{\eta}_{n-1}^{t-1})^T + \left(I - \bar{\varepsilon}_{n-1}^{t}(\bar{\varepsilon}_{n-1}^{t})^T\right)^{\frac{1}{2}} \rho_n^{t-1}\left(I - \bar{\eta}_{n-1}^{t-1}(\bar{\eta}_{n-1}^{t-1})^T\right)^{\frac{1}{2}}$$

$$\bar{\varepsilon}_n^{t} = \left(I - \rho_n^{t}(\rho_n^{t})^T\right)^{-\frac{1}{2}}\left(\bar{\varepsilon}_{n-1}^{t} - \rho_n^{t}\,\bar{\eta}_{n-1}^{t-1}\right)\left(I - (\bar{\eta}_{n-1}^{t-1})^T\bar{\eta}_{n-1}^{t-1}\right)^{-\frac{1}{2}}$$

$$\bar{\eta}_n^{t} = \left(I - (\rho_n^{t})^T\rho_n^{t}\right)^{-\frac{1}{2}}\left(\bar{\eta}_{n-1}^{t-1} - (\rho_n^{t})^T\bar{\varepsilon}_{n-1}^{t}\right)\left(I - (\bar{\varepsilon}_{n-1}^{t})^T\bar{\varepsilon}_{n-1}^{t}\right)^{-\frac{1}{2}}$$

These recursions were derived both algebraically [2] and geometrically [2], [3]. However this first geometric derivation was rather lengthy and presented the disadvantage to make a clear distinction between, on the one hand, the order recursive equations (1-b), (1-c); and on the other hand, the pure time-update (1-a), the derivation of which needed to introduce a complicated decomposition of some orthogonal projection in terms of oblique projections.

Both derivations were reconciled in a most elegant way [4] when it appeared that (1-b), (1-c) as well as a reordering (1-d) of (1-a) :

$$\rho_n^{t-1} = \left(I - \bar{\varepsilon}_{n-1}^{t}(\bar{\varepsilon}_{n-1}^{t})^T\right)^{-\frac{1}{2}}\left(\rho_n^{t} - \bar{\varepsilon}_{n-1}^{t}(\bar{\eta}_{n-1}^{t-1})^T\right)\left(I - \bar{\eta}_{n-1}^{t-1}(\bar{\eta}_{n-1}^{t-1})^T\right)^{-\frac{1}{2}}$$

were 3 particular applications of a general identity among partial correlation coefficients, first discovered (in the scalar case) by Yule [5].

In this paper, we first gather the 3 fundamental planar biorthogonalization steps which underlie the RLS adaptive lattice in a 3D unit-length tetrahedron. YPII then receives a nice new geometric interpretation in terms of projections into this tetrahedron.

Now, tetrahedrons and spherical triangles are closely related figures in the 3D space. Deriving projective identities into tetrahedrons thus amounts to deriving trigonometric relations on the sphere. It then happens that *YPII is indeed the fundamental cosine law of spherical trigonometry*. In that new geometrical framework, the old, classical angle-normalized RLS lattice algorithm happens to be one particular solution to one of the six spherical triangle problems.

Furthermore, the formulae of spherical trigonometry induce, by analogy, similar recursions among parcors. For instance, the cosine law in the polar triangle leads to an original "dual" version of YPII.

2 - UPDATING OF PROJECTION OPERATORS AND PLANAR BIORTHOGONALIZATION STEPS

The following derivation can be formalized in any Hilbert space (since we are just concerned with projection identities), and more specifically in the space $L^2(\Omega, A, P)$ of square-integrable random variables with inner product $(X,Y) = E(XY^T)$. In this paper, we will adopt the perhaps more familiar alternative viewpoint of deterministic adaptive filtering. The framework is thus the space R^N of $N-$dimensional vectors. More generally, for reasons to become clear soon, X (and also Y, A, B, C) will denote in the sequel any arbitrary aggregate of n_X $(1 \le n_X \le N)$ $N-$dimensional vectors (see e.g. [3] for details); the inner product among X and Y is defined as $(X,Y) = X^T Y$; X is orthogonal to Y $(X \perp Y)$ if $(X,Y) = 0_{n_X \times n_Y}$.

The linear combination $\hat{x}$ of a set of vectors $Y = [y_1 \cdots y_{n_Y}]$ that best fits (in a LS sense : $\| x - \hat{x} \|$ min) a vector x is well known to be the projection of x onto the space spanned by the vectors of Y. Thus LS filtering is intimately connected with projecting onto a vector space. *Recursive* LS filtering is concerned with updating the optimal solution on arrival of new data; it thus amounts to updating projection operators. Let $P_X = X(X^T X)^{-1} X^T$ denote the projection operator onto the space spanned by X, and

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$P_X^\perp = I - X(X^TX)^{-1}X^T$ its orthogonal complement[1]. Now, a key tool for updating projection operators is the fact that the projection onto the augmented subspace (X,Y) is equal to the projection onto X, plus the projection onto that part of Y which is orthogonal to X :

$$P_{X,Y} = P_X + P_X^\perp Y\left(Y^T P_X^\perp Y\right)^{-1} Y^T P_X^\perp \qquad \text{(2-a)}$$

$$\boxed{P_{X,Y}^\perp = P_X^\perp - P_X^\perp Y\left(Y^T P_X^\perp Y\right)^{-1} Y^T P_X^\perp} \qquad \text{(2-b)}$$

These identities are of utmost importance in RLS adaptive filtering as well as in Kalman filtering.

Let us now recall some known results [6], [7]. From (2-b), we see that we can go from $P_Y^\perp A$ to $P_{Y,B}^\perp A$ with the help of $P_Y^\perp B$:

$$\underbrace{P_{Y,B}^\perp A} = \underbrace{P_Y^\perp A} - \underbrace{P_Y^\perp B}\left(B^T P_Y^\perp B\right)^{-1}\left(B^T P_Y^\perp A\right) \qquad \text{(3-a)}$$

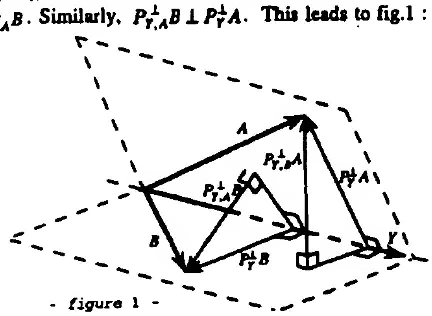
apart from the obvious orthogonality relationships :

$$P_Y^\perp A \perp Y \ , \ P_Y^\perp B \perp Y \ , \ P_{Y,B}^\perp A \perp Y,B$$

there appears a new one among the 3 above vectors :

$$P_{Y,B}^\perp A \perp P_Y^\perp B \qquad \text{(3-b)}$$

Now, from the 2 elementary residuals $P_Y^\perp A$, $P_Y^\perp B$ used in (3-a), we can construct as well the 2[nd] augmented residual $P_{Y,A}^\perp B$. Similarly, $P_{Y,A}^\perp B \perp P_Y^\perp A$. This leads to fig.1 :



- figure 1 -

The coupled recursions $(P_Y^\perp A, P_Y^\perp B) \rightarrow (P_{Y,A}^\perp B, P_{Y,B}^\perp A)$ are thus a "planar"[2] biorthogonalization process (4) :

$$\left[P_{Y,B}^\perp A \quad P_{Y,A}^\perp B\right] =$$

$$\left[P_Y^\perp A \quad P_Y^\perp B\right]\begin{bmatrix} I & -\left(A^T P_Y^\perp A\right)^{-1}\left(A^T P_Y^\perp B\right) \\ -\left(B^T P_Y^\perp B\right)^{-1}\left(B^T P_Y^\perp A\right) & I \end{bmatrix}$$

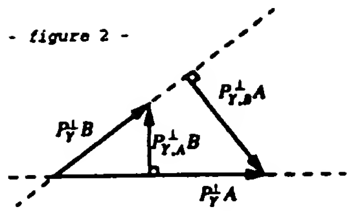
with $\quad P_{Y,B}^\perp A \perp P_Y^\perp B \ , \ P_{Y,A}^\perp B \perp P_Y^\perp A$.

This is maybe best visualized by fig.2, drawn out of fig.1 (for the 2 right triangles lie in parallel planes):

1 whatever the projection operator considered, we suppose that X^TX is invertible (otherwise we can take generalized inverses [8])

2 Since Y, A and B lie in 3 disjoint subspaces of R^N (the null vector is the only vector commun to any two out of these three subspaces), they are *visualized* by non-coplanar vectors in fig.1 which, necessarily, is 3-dimensional. On the other hand, both $P_{Y,B}^\perp A$ and $P_{Y,A}^\perp B$ lie in the space spanned by the 2 "vectors" $P_Y^\perp A$ and $P_Y^\perp B$ (actually a $N x n_A$ and a $N x n_B$ matrix, respectively); whence the (improper) use of the term "planar".

- figure 2 -



It will soon be necessary to manipulate normalized residuals, defined as[3] :

$$\overline{P_Y^\perp A} \stackrel{\Delta}{=} P_Y^\perp A\left(A^T P_Y^\perp A\right)^{-\frac{T}{2}} \qquad \text{(5-a)}$$

in which $M^{1/2}$ denotes any square-root of the positive definite matrix M, i.e., $M^{\frac{1}{2}}(M^{\frac{1}{2}})^T \stackrel{\Delta}{=} M^{\frac{1}{2}}M^{\frac{T}{2}} = M$. Then we have :

$$\left(\overline{P_Y^\perp A}\right)^T \overline{P_Y^\perp A} = I_{n_A x n_A} \ , \ P_{\overline{P_Y^\perp A}} = \overline{P_Y^\perp A}\left(\overline{P_Y^\perp A}\right)^T = P_{P_Y^\perp A} \qquad \text{(5-b,c)}$$

(4) admits the normalized version (6-a,b) :

$$\left[\overline{P_{Y,B}^\perp A} \ \overline{P_{Y,A}^\perp B}\right] =$$

$$\left[\overline{P_Y^\perp A} \ \overline{P_Y^\perp B}\right]\begin{bmatrix} I & -\rho \\ -\rho^T & I \end{bmatrix}\begin{bmatrix} \left(I-\rho\rho^T\right)^{-\frac{T}{2}} & 0 \\ 0 & \left(I-\rho^T\rho\right)^{-\frac{T}{2}} \end{bmatrix}$$

in which $\rho = \rho_Y(A,B)$ is the PARCOR (7):

$$\rho_Y(A,B) \stackrel{\Delta}{=} \left(\overline{P_Y^\perp A}, \overline{P_Y^\perp B}\right)$$

$$= \left(A^T P_Y^\perp A\right)^{-\frac{1}{2}}\left(A^T P_Y^\perp B\right)\left(B^T P_Y^\perp B\right)^{-\frac{T}{2}} = \rho_Y^T(B,A)$$

and we used the identity (8) :

$$\left(B^T P_Y^\perp B\right)^{-\frac{1}{2}}\left(B^T P_{Y,A}^\perp B\right)^{\frac{1}{2}} = \left(I - \rho_Y(B,A)\rho_Y(A,B)\right)^{\frac{1}{2}}$$

which is soon derived from (2-b).

3 - YULE'S PARCOR IDENTITY IN THE UNIT-LENGTH 3D TETRAHEDRON

Yule's PARCOR Identity is a formula that expresses the augmented parcor $\rho_{Y,A}(C,B)$, say, in terms of the elementary ones $\rho_Y(A,C)$, $\rho_Y(B,A)$ and $\rho_Y(C,B)$. It is simply derived by pre- (post-) multiplying (2-b) by $\left(C^T P_Y^\perp C\right)^{-\frac{1}{2}} C^T$ (by $B\left(B^T P_Y^\perp B\right)^{-\frac{T}{2}}$), and by using (7), (8) (see [8], Annex A, for details) :

$$\rho_{Y,A}(C,B) = \left(I - \rho_Y(C,A)\rho_Y(A,C)\right)^{-\frac{1}{2}} \times$$
$$\left(\rho_Y(C,B) - \rho_Y(C,A)\rho_Y(A,B)\right) \times \left(I - \rho_Y(B,A)\rho_Y(A,B)\right)^{-\frac{T}{2}} \qquad \text{(9)}$$

(9) admits the reordered (sometimes called "inverse") version :

$$\rho_Y(C,B) = \rho_Y(C,A)\rho_Y(A,B) + \left(I - \rho_Y(C,A)\rho_Y(A,C)\right)^{\frac{1}{2}} \times$$
$$\rho_{Y,A}(C,B) \times \left(I - \rho_Y(B,A)\rho_Y(A,B)\right)^{\frac{T}{2}} \qquad \text{(10)}$$

(9) and (10) are fundamental in RLS lattice filtering, since the angle-normalized lattice recursions (1) are nothing but particular applications of (9) (or (10)). More precisely, let $\{y_i\}$ be a m-dimensional process. Define the $(t+1)xm$ matrix $y_{t-p} = [0 \cdots 0 y_0 \cdots y_{t-p}]^T$ (the p first rows are zeros), and the $(t+1)x1$ vector $\sigma = [0 \cdots 01]^T$ (the "pinning vector"). Then (1) is

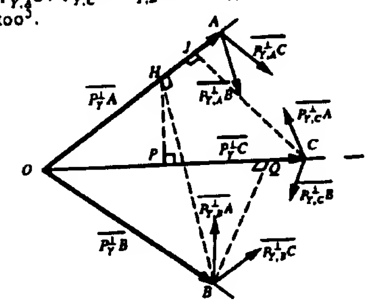
3 we assume that $A^T P_Y^\perp A$ is positive definite. The positive semi-definite case is treated in [8].

obtained from (9) by setting $Y=[y_{t-1} \cdots y_{t-n+1}]$, and by replacing (A,B,C) by the following permutations of (y_t, y_{t-n}, σ) [4], [9]:

	A	B	C
(1-b)	y_{t-n}	σ	y_t
(1-c)	y_t	σ	y_{t-n}
(1-d)	σ	y_{t-n}	y_t

Now, transformations among residual vectors induce transformations among the filters which produced these residuals. Consequently, the FRLS *transversal* filter recursions are derived by considering the 3 particular applications of (6), when we take for A and B any 2 aggregates out of the set (y_t, y_{t-n}, σ) [9], [7]. On the other hand, the FRLS angle-normalized *lattice* recursions are the 3 particular applications of (9) or (10), obtained by taking the inner product of (6-a), written for 2 particular aggregates taken out of the same set (y_t, y_{t-n}, σ), by that same formula, written for another 2 aggregates [9] (3 possibilities : $(\overline{P^{\perp}_{Y,y_t} y_{t-n}}, \overline{P^{\perp}_{Y,y_t} \sigma})$; $(\overline{P^{\perp}_{Y,y_{t-n}} y_t}, \overline{P^{\perp}_{Y,y_{t-n}} \sigma})$; $(\overline{P^{\perp}_{Y,\sigma} y_t}, \overline{P^{\perp}_{Y,\sigma} y_{t-n}})$.). Note that a similar approach was used in [6].

This suggests that the geometric figure that best represents the FRLS problem, in both transversal and lattice structures, might be the 3D unit-length tetrahedron $(\overline{P^{\perp}_Y y_t}, \overline{P^{\perp}_Y y_{t-n}}, \overline{P^{\perp}_Y \sigma})$ - or, more generally, $(\overline{P^{\perp}_Y A}, \overline{P^{\perp}_Y B}, \overline{P^{\perp}_Y C})$ of fig.3[4]. In general, one cannot visualize more than three disjoint subspaces of R^N. However, in view of fig.2 (or recursions (6)), the 6 augmented residuals $\overline{P^{\perp}_{Y,A} B}$, $\overline{P^{\perp}_{Y,B} A}$, $\overline{P^{\perp}_{Y,A} C}$, $\overline{P^{\perp}_{Y,C} A}$, $\overline{P^{\perp}_{Y,B} C}$ and $\overline{P^{\perp}_{Y,C} B}$ take place in the same figure too[5].



- figure 3 -

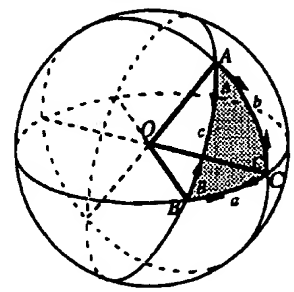
In the annex, we rederive (10) (i.e., YPII) in terms of projections inside this tetrahedron. More precisely, we show that the "length" of $\overrightarrow{OQ}$, where Q is the orthogonal projection of B onto A, is equal to $\rho_Y(C,B)$, the l.h.s. of (10). Now, B can be first projected onto $\overrightarrow{OA}$, resulting in H, and H can again be projected onto $\overrightarrow{OC}$, which gives P. This results in decomposing $\overrightarrow{OQ}$ as $\overrightarrow{OP}+\overrightarrow{PQ}$. This decomposition corresponds exactly to the two-terms sum of the r.h.s. of (10), i.e., the length OP of $\overrightarrow{OP}$ is equal to $\rho_Y(C,A)\rho_Y(A,B)$, while the 2^{nd} term of the r.h.s. of (10) is equal to the length of $\overrightarrow{PQ}$.

4 as far as notations are concerned, the same letter A is used for an aggregate of vectors; for the extremity of $\overline{P^{\perp}_Y A}$ in the representation of fig.3; and, in the following, for a point on the sphere as well as for an angle, in fig.4. The true meaning should be clear from the context.

5 in order to maintain clarity, we just represented the direction of those 6 vectors (they are actually of length one).

4 - CONNECTIONS WITH SPHERICAL TRIGONOMETRY

Tetrahedrons (and thus spherical trigonometry) play the same fundamental role in solid geometry as triangles (and thus classical trigonometry) in planar geometry [10]. Spherical trigonometry is a tool of outstanding importance in astronomy and navigation on ships or airplanes (however, connections with RLS adaptive filtering had never been made so far!). To see how things are related, notice (see fig.4) that any 3 points on the 3D unit sphere determine : either the unit-length tetrahedron $OABC$ (i.e., length(OA) = length(OB) = length(OC) = 1) - and thus our projection (RLSL) problem; or the *spherical triangle ABC* - and thus spherical trigonometry.



- figure 4 -

By definition, the spherical triangle ABC consists of the 3 arcs AB, AC and BC of "great circles" obtained by intersecting the 3 planes OAB, OAC, OBC (i.e., which pass through the center O of the sphere) and the sphere. The angle BOC is equal to the length of arc BC and is denoted by a. We call A the dihedral angle between planes OAB and OAC, defined as the plane angle between 2 straight lines orthogonal to OA, and belonging respectively to OAB and OAC. Note that A is equal to the plane angle formed by tangents to the side of the angle at vertex A, and similarly for the remaining angles.

There are 3 degrees of freedom in a spherical triangle : any 3 angles (out of 6) perfectly determine the 3 remaining ones. Consequently, there cannot be more than 3 distinct relationships among the 6 angles. To get one such set, let us now revisit the derivation of (10) as given in the annex (which actually was inspired by [11]), but now considering fig.4 as well as fig.3. $OQ = \cos a$, $OP = \cos b \cos c$, and $(\overrightarrow{HB}, \overrightarrow{OC}) = (\overrightarrow{HB}, \overrightarrow{OJ}+\overrightarrow{JC}) = (\overrightarrow{HB}, \overrightarrow{JC}) = \sin b \sin c \cos A$. We just derived the fundamental "law of cosines" of spherical trigonometry :

$$\cos a \;=\; \cos b \cos c \;+\; \sin b \cos A \sin c \qquad \text{(11-a)}$$

which thus happens to be equal to the YPII (in the scalar case), through the identification[6] (12) :

$$\begin{array}{llll} \cos a \leftrightarrow \rho_Y(C,B) & & \cos A \leftrightarrow \rho_{Y,A}(C,B) \\ \cos b \leftrightarrow \rho_Y(C,A) & & \cos B \leftrightarrow \rho_{Y,B}(C,A) \\ \cos c \leftrightarrow \rho_Y(A,B) & & \cos C \leftrightarrow \rho_{Y,C}(A,B) \end{array}$$

6 $\forall\, Y, A, B$, the spectral norm of $\rho_Y(A,B)$ is inferior or equal to 1 [8].

since (11-a) remains valid under permutation of the variables, we get[7] :

$$\cos b \;=\; \cos a \cos c \;+\; \sin a \cos B \sin c \qquad (11\text{-b})$$

$$\cos c \;=\; \cos a \cos b \;+\; \sin a \cos C \sin b \qquad (11\text{-c})$$

In that framework, the angle-normalized RLSL is one particular solution to one of the six "spherical triangle problems" (i.e., determining any 3 angles from the 3 other angles) [12], [13] : "given 2 arcs b and c, plus an angle in-between A, find the third arc a and the two remaining dihedral angles B and C". To see this, set as above $Y = \left[y_{t-1} \cdots y_{t-n+1}\right]$, and $(A,B,C) = (\sigma, y_{t-n}, y_t)$. At time $t-1$, we know the angles b, c and A (actually their cosines) :

$$\cos b = \bar{\varepsilon}^{t}_{n-1} \quad , \quad \cos c = \bar{\eta}^{t-1}_{n-1} \quad , \quad \cos A = \rho^{t-1}_{n}$$

We first compute $\cos a = \rho^{t}_{n}$ through (11-a) = (1-a), then $\cos B = \bar{\varepsilon}^{t}_{n}$ and $\cos C = \bar{\eta}^{t}_{n}$ via (11-b) = (1-b) and (11-c) = (1-c), respectively.

A "dual" version of YPII

Now, the formulae of spherical trigonometry [10-13] induce, by analogy, similar formulaes among parcors. For instance, consider the 2 great circles having as poles B and C. They intersect in 2 points A' and A''. Let A' be the point on the same side as A (and similarly for B' and C'). We just defined the so-called "polar triangle" $A'B'C'$ of ABC. In this triangle, the angles a' and A' are equal to $\pi - A$ and $\pi - a$, respectively (and similarly for the other angles); the cosine law reads :

$$\cos A \;=\; -\cos B \cos C \;+\; \sin B \cos a \sin C \qquad (12)$$

This suggests the following formula among parcors (13):

$$\rho_{Y,A}(C,B) = -\rho_{Y,B}(C,A)\rho_{Y,C}(A,B) + \left(I - \rho_{Y,B}(C,A)\rho_{Y,B}(A,C)\right)^{\frac{1}{2}} \times$$

$$\rho_Y(C,B) \times \left(I - \rho_{Y,C}(B,A)\rho_{Y,C}(A,B)\right)^{\frac{1}{2}}$$

indeed, (13) does hold for scalar parcors (A, B and C are $N \times 1$). It is derived by considering once again the proof given in the annex, but now in the "polar tetrahedron" $\overline{P^{\perp}_{Y,B,C}A}$, $\overline{P^{\perp}_{Y,C,A}B}$, $\overline{P^{\perp}_{Y,A,B}C}$. Notice that :

$$\left(\overline{P^{\perp}_{Y,A,B}C}, \overline{P^{\perp}_{Y,C,A}B}\right) = \left(I - \rho_{Y,A}(C,B)\rho_{Y,A}(B,C)\right)^{-\frac{1}{2}} \times$$

$$\left(-\rho_{Y,A}(C,B)\right)\left(I - \rho_{Y,A}(B,C)\rho_{Y,A}(C,B)\right)^{\frac{1}{2}}$$

which reduces to $-\rho_{Y,A}(C,B)$ in the scalar case, whence (13).

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ANNEX

Let H be the orthogonal projection of B onto $\overrightarrow{OA}$. With the help of fig.2, $\overrightarrow{OB} = \overrightarrow{OH} + \overrightarrow{HB}$ reads (A1) :

$$\overline{P^{\perp}_Y B} = P_{\overline{P^{\perp}_Y A}}\left(\overline{P^{\perp}_Y B}\right) + P^{\perp}_{\overline{P^{\perp}_Y A}}\left(\overline{P^{\perp}_Y B}\right) = P_{\overline{P^{\perp}_Y A}}\left(\overline{P^{\perp}_Y B}\right) + P_{\overline{P^{\perp}_{Y,A} B}}\left(\overline{P^{\perp}_Y B}\right)$$

Let us project this decomposition $\overrightarrow{OB} = \overrightarrow{OH} + \overrightarrow{HB}$ onto the third vector $\overrightarrow{OC}$ of the tetrahedron:

$$P_{\overline{P^{\perp}_Y C}}\left(\overline{P^{\perp}_Y B}\right) = P_{\overline{P^{\perp}_Y C}}\left(P_{\overline{P^{\perp}_Y A}}\left(\overline{P^{\perp}_Y B}\right)\right) + P_{\overline{P^{\perp}_Y C}}\left(P_{\overline{P^{\perp}_{Y,A} B}}\left(\overline{P^{\perp}_Y B}\right)\right) \qquad (A2)$$

Now, we would like to express the fact that the relationship (A2) among vectors remains valid when considering their length, since $\overrightarrow{OP}$, $\overrightarrow{OQ}$ and $\overrightarrow{PQ}$ are colinear : $OQ = OP + PQ$ (the sum is algebraic). To that end, let us pre-multiply (A2) by $\left(\overline{P^{\perp}_Y C}\right)^T$. We get (A3-a) :

$$\left(\overline{P^{\perp}_Y C}\right)^T \left\{\left(\overline{P^{\perp}_Y B}\right) = \left(\overline{P^{\perp}_Y A}\right)\left(\overline{P^{\perp}_Y A}\right)^T \left(\overline{P^{\perp}_Y B}\right) + P_{\overline{P^{\perp}_{Y,A} B}}\left(\overline{P^{\perp}_Y B}\right)\right\}$$

Introducing the parcors via (7), (A3-a) becomes (A3-b) :

$$\rho_Y(C,B) = \rho_Y(C,A)\rho_Y(A,B) + \left(\overline{P^{\perp}_Y C}\right)^T P_{\overline{P^{\perp}_{Y,A} B}}\left(\overline{P^{\perp}_Y B}\right)$$

To get further, let us consider the orthogonal decomposition $\overrightarrow{OC} = \overrightarrow{OJ} + \overrightarrow{JC}$. The second term of the r.h.s. of (A3-b) can be rewritten as (A4) :

$$\left(C^T P^{\perp}_Y C\right)^{-\frac{1}{2}} \underbrace{\left[C^T P^{\perp}_{Y,A} + C^T P^{\perp}_Y A \left(A^T P^{\perp}_Y A\right)^{-1} A^T P^{\perp}_Y\right]}_{C^T P^{\perp}_Y} P_{\overline{P^{\perp}_{Y,A} B}}\left(\overline{P^{\perp}_Y B}\right)$$

Since $\overrightarrow{HB} \perp \overrightarrow{OJ}$, the second term in the above inner-product is zero. Thus (A4) reduces to (A5) :

$$\left(C^T P^{\perp}_Y C\right)^{-\frac{1}{2}} C^T P^{\perp}_{Y,A} \times P^{\perp}_{Y,A} B \left(B^T P^{\perp}_Y B\right)^{-\frac{1}{2}}$$

where we used fig.2. Using (8), (A5) is rewritten as (A6):

$$\left(I - \rho_Y(C,A)\rho_Y(A,C)\right)^{\frac{1}{2}} \rho_{Y,A}(C,B) \left(I - \rho_Y(B,A)\rho_Y(A,B)\right)^{\frac{1}{2}}$$

Gathering (A3-b) and (A6) results in (10).

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7 due to the above remark, any other formula can be deduced from (11-a,b,c). For this reason (11-a,b,c) are often called the fundamental laws of spherical trigonometry.

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